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Analysis of friction reduction effect due to ultrasonic vibration exerted in friction stir welding

C.L. Yang, C.S. Wu*, L. Shi

MOE Key Lab for Liquid-Solid Structure Evolution and Materials Processing, Institute of Materials Joining, Shandong University, Jinan, 250061 China

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ABSTRACT

A model is developed to characterize the ultrasonic induced friction reduction in ultrasonic vibration enhanced friction stir welding (UVeFSW). Two effects, i.e., acoustic softening and ultrasonic induced friction reduction (UiFR), are both considered in analyzing the heat generation, temperature profile and material flow in UVeFSW. It is found that at the tool/workpiece contact interfaces the friction coefficient shows a butterfly-like distribution if the ultrasonic induced friction reduction (UiFR) is taken into consideration. With UiFR, the predicted heat generation in UVeFSW is more reasonable, the predicted TMAZ (thermo-mechanically affected zone) boundary is in more agreement with the measured one, and the calculated thermal cycles match better with the experimentally measured ones.

1. Introduction

As a solid state joining process, friction stir welding (FSW) has been proved to be energy efficient, environment friendly and versatile in manufacturing lightweight structures [1,2]. During FSW process, the heat generation caused by friction between the tool and the workpiece and plastic deformation of workpiece near the tool pin is utilized to soften the material around the pin, and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin so that a joint is formed [2]. Thus, in conventional FSW large spindle torque and downward force are needed to generate the necessary heat energy and material softening to facilitate sufficient plastic material flow near the tool [2,3]. To lower the required welding loads, various kinds of secondary energy sources, such as arc, laser, induction heat, etc., are used to assist local softening of the material to be welded by FSW process [4]. Ultrasonic vibration, as mechanical energy, offers quite a few advantages in assisting FSW [4,5].

Researchers tried different ways to exert ultrasonic vibration into FSW process, and found that ultrasonic vibration improves the FSW weld quality, reduces the welding force and increases the fluidity of plastic material [6–8]. The authors' group developed ultrasonic vibration enhanced FSW (UVeFSW) to transmit ultrasonic vibration energy directly into the workpiece ahead of the FSW tool [9], and found that in UVeFSW the plastic material flow is enhanced, the welding loads are reduced, and microstructure & mechanical properties of the joints are improved [9–14].

There are a few explanations for the effects of ultrasonic vibration on the metal processing, including the stress superposition [15], the acoustic softening [16], and the friction reduction at the interface due to the exerted ultrasonic vibration [17]. Shi et al proposed a modified material constitutive equation characterizing the acoustic softening effect on aluminum alloys in UVeFSW by considering the thermal activation of dislocation under the influence of ultrasonic energy [18]. It reveals that the ultrasonic vibration energy density reduces the activation energy for deformation, resulting in a decrease of the flow stress during hot plastic deformation with superimposed ultrasonic vibration. Then, the modified constitutive equation was implemented into a CFD model of UVeFSW. It is found that the coupling of high ultrasonic energy near and in front of the FSW tool with the plastic deformed material pre-softened the material, resulting in a lower flow stress and viscosity [19]. However, it did not account for the friction reduction effect due to the relative motion at the interface between the tool and the material in the shear layer.

During FSW process, the friction coefficient between the tool and the material in the shear layer determines the heat generation which plays an important role in the softening and plastic deformation of the material to be welded. The influence of the exerted ultrasonic vibration on the friction coefficient at the tool/workpiece interface, i.e., the friction reduction effect due to ultrasonic vibration in UVeFSW process must be taken into consideration. Thereby, this study aims at the effect of ultrasonic deduced friction reduction on the UVeFSW process.

In this paper, both the acoustic softening effect and the friction

* Corresponding author.
E-mail address: wucs@sdu.edu.cn (C.S. Wu).

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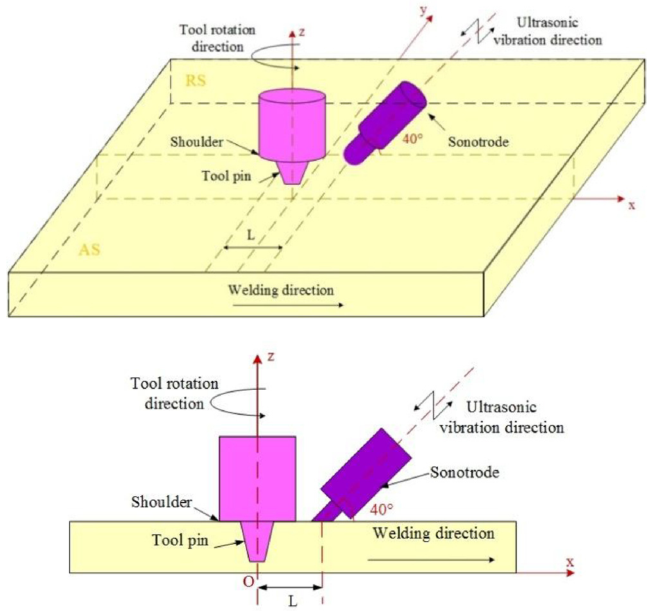

Fig. 1. Schematic of UVeFSW process.

reduction effect due to the exerted ultrasonic vibration are considered in modeling the UVeFSW process. The effects of ultrasonic vibration on friction reduction in UVeFSW process and consequent impact on the heat generation, material flow and temperature field have been quantitatively analyzed. The numerical simulation results are experimentally validated by comparing the thermo-mechanically affected zone (TMAZ) boundaries and the thermal cycles.

2. Experiment

Fig. 1 shows the schematic of the experimental UVeFSW system. During the UVeFSW process, the ultrasonic vibration is directly transmitted into the local workpiece (ahead of the tool) by a sonotrode. The vibration frequency is 20 kHz, the amplitude is 40 μm and the efficient power is 300 W. The radius of the sonotrode at the tip is 4.0 mm. The sonotrode is 20 mm ahead of the FSW tool, inclined at 40° with respect to the horizontal axis. The clamping force of the sonotrode is 300 N during the UVeFSW process.

Both conventional FSW and UVeFSW tests were conducted to weld the plates of aluminum alloy 6061-T6. The chemical compositions of AA6061-T6 are listed in Table 1. The plates were 300 mm in length, 80 mm in width and 6 mm in thickness, polished and cleaned by acetone at the top, bottom and abutting surfaces before welding. The FSW tool constituted a 15 mm diameter shoulder and a frustum-shaped right-hand threaded pin (tip diameter 3.2 mm, root diameter 5.6 mm and length 5.7 mm), and its material was steel H13. The tool was rotated anticlockwise with a tilt angle 2.5°. The tool rotation speed, the welding speed, and the plunge depth of shoulder were 800 rpm, 240 mm/min, and 0.1 mm, respectively.

After welding, the transverse cross-section specimens of the joints were prepared according to the standard metallographic procedures, etched with the Keller reagent, to characterize their macrostructure by optical microscopy.

Table 1
Chemical composition of 6061-T6.

wt%	Al	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Others
6061	Balance	0.9	0.6	0.55	0.3	0.15	0.3	0.25	0.15	0.15

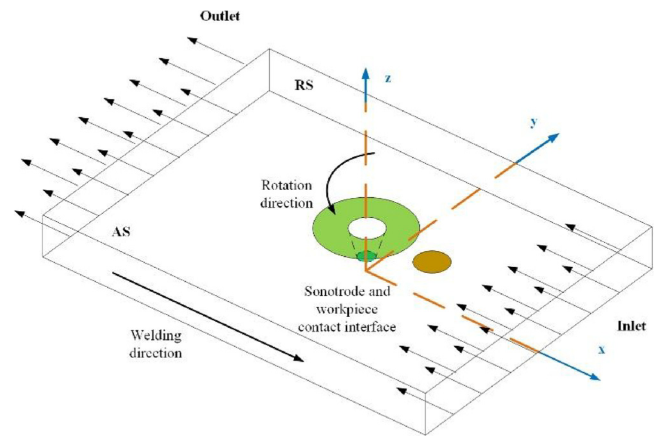

Fig. 2. The geometry model of UVeFSW process.

3. Formulation

A geometrical model for UVeFSW process simulation is shown in Fig. 2. A 3D Cartesian coordinate system was established on the plate with its origin located at the bottom surface of the workpiece under the axis of the tool, the x-axis is along the joint line, and the z-axis is normal to the top surface of workpiece.

For simplification, the tilt angle of the tool and the shoulder plunge depth were taken as zero, and the tool shoulder was assumed to be flat. The material was assumed to behave as an incompressible and single-phase non-Newtonian visco-plastic fluid, and only the plastic deformation was considered.

Since it is time-consuming for a transient model to achieve a quasi-steady state, first a quasi-steady state model was developed for the conventional FSW. The converged computation results of the above quasi-steady state model were taken as the initial conditions of transient state model to calculate ultrasonic energy density field, thermal processes and material flow during UVeFSW.

3.1. Governing equations

The continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\rho\vec{v} = 0 \tag{1}$$

where ρ is the density, t is the time, and $\vec{v}$ is the material flow velocity vector with its components (u, v, w).

The momentum equation

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla\cdot\rho\vec{v}\vec{v} = -\nabla\cdot p + \nabla\cdot[\mu_s(\nabla\vec{v} + \nabla\vec{v}^{\mathrm{T}})] \tag{2}$$

where p is the pressure, and μ_s is the non-Newtonian viscosity.

The energy equation,

$$\rho C_p\vec{v}\cdot\nabla T = \nabla\cdot(k\nabla T) + S_v \tag{3}$$

where C_p is the specific heat, T is the temperature, k is the thermal conductivity, and S_v is the viscous dissipation source, which can be expressed as [20]:

$$S_v = \beta\mu_s\bar{\varepsilon}^2 \tag{4}$$

where β represents the efficiency of viscous dissipation converted to heat, and $\bar{\varepsilon}$ is the effective strain rate which can be written as,

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